Telecommunications for Mars Rovers and Robotic Missions

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Abstract

The Mars exploration program of' NASA and the international community will evolve from an early emphasis on orbital remote sensing toward in situ science activity on, or just above, the Martian surface. Key surface science objectives, including life science, will require mobility, thus dictating an increasing role for planetary rovers. Telecommunications will play an enabling role in achieving the objectives of these rovers as well as other surface elements. End-to-end telecommunications may be accomplished by direct links from the Martian surface to antennas of the Deep Space Network (DSN) on Earth or by means of relay links provided by spacecraft in Mars orbit, Power and mass constraints on landed elements at Mars strongly favor the use of relay communications. This paper reviews current plans for Mars missions through the 2005 launch opportunity and examines their capabilities to support rovers and other landed elements via relay communications. The review provides Mars rover and lander designers with information useful in developing communications subsystems for incorporation into their overall systems designs.

Introduction

Telecommunications plays a key role in all rover and other robotic missions to Mars both as a conduit for command information to the spacecraft and for the return of scientific data from the instruments and engineering data from the spacecraft. Telecommunications to the Earth may be accomplished using direct-to-Earth links via the Deep Space Network (DSN) or by means of relay links provided by orbital missions at Mars. A number of factors make direct-to-Earth telecommunications for robotic or rover missions at Mars very challenging, especially for small systems [1, 2]. These include the distance between Mars and Earth, the inability of Earth-based systems to regularly communicate to all portions of Mars, the power and mass constraints on systems at Mars along with the substantial power and/or antenna requirements. By decreasing the communications range and providing coverage to virtually all portions of the Martian surface, orbiting missions with telecommunications relay systems can send and receive large amounts of data to and from rover missions and relay these data to and from Earth. These orbiting relay systems are viewed as enabling elements as they provide telecommunications support for multiple missions including extremely constrained missions, such as micro rovers or balloons.

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With the launch of Mars Global Surveyor (MGS) and Mars Pathfinder the next generation of Mars exploration has begun. Over the next decade, the Mars Exploration Program [3], led by the National Aeronautics and Space Administration (NASA) and the Jet Propulsion Laboratory (JPL), will launch one or more missions to Mars during each of the launch opportunities in 1998, 2001, 2003, and 2005 [4, 5]. Of these, the orbiting missions, starting with MGS, will each carry a UHF communications package that will provide a relay link to and from appropriately equipped landed elements. The relay capability will vary with each mission but will enable and enhance small, low-power telecommunications systems for robotic assets on or near the surface, such as rovers and balloons.

This paper considers the relay capabilities of MGS, the Mars Surveyor Program (MSP) '98 Orbiter, and future orbiters. The discussion will include both link design considerations and multi-mission support operations necessary for rover and robotic designs based on results from a JPL-led study of relay communications at Mars. In addition to the telecommunications support, the relay systems of the orbiters can also provide navigation and location services to robotic missions.

Mars Exploration Program and Orbiter Relay Capabilities

The successful launches of Mars Global Surveyor (MGS) and Mars Pathfinder commence the next generation in Mars exploration. Due to the synodic period of Mars and Earth, future opportunities for launching missions to Mars exist in late 1998, early 2001, 2003, and 2005. To take advantage of these opportunities, NASA and the international community plan a series of missions to explore Mars using both orbiting and landed elements. Figure 1 provides an overview of the planned missions as of early January 1997. Due to the volatility in planning future missions, the projects after 1998 outlined in the mission scenario should be considered preliminary, but the intent to launch missions during each of the launch opportunities is firm.

The multi-mission character of the Mars exploration program enables the possibility of coordinating missions. An important facet of this coordination is the inclusion of in situ relay capability in Mars orbit that can support landed and atmospheric missions. The relay service can not only enhance landed systems with increased telemetry and command transmissions but also enable small robotic missions that otherwise could not communicate with Earth. Figure 2 provides a view of the relay concept and defines terminology for links used in this paper. Consequently, starting with MGS, a communication relay package will be included on most of the planned orbiting missions at Mars. In addition, NASA and JPL have studied the possibility of inexpensive dedicated relay satellites for the sole purpose of supporting multiple missions, including rovers [2, 6].

One good example of the type of mission that a relay system can make possible is the NASA New Millennium Program's Mars Microprobe [7-8]. The Mars Microprobe, which will travel on the Mars Surveyor Program (MSP) '98 Lander, is an extremely constrained mission due to its small size and limited power. Its mission is to penetrate, rather than "land," on the surface of Mars. Communication direct-to-Earth is impossible for such a system, but a relay link to an orbiting system can be designed. The Mars Microprobe will communicate. with the Mars Relay (MR), a UHF system on MGS. The communication parameters for this mission are described in a subsequent section.

The following sub-sections describe the planned Mars orbiter missions, their relay capabilities, and any associated missions using the relays. These descriptions include existing or planned communication parameters. In addition to the communication parameters, the descriptions also include information about the. orbiting spacecraft and its specific orbit that robotic mission telecommunication designers need to know to take advantage of these systems. A subsequent section will examine the communication parameters and associated factors and provide an overview of the support that these missions can provide.

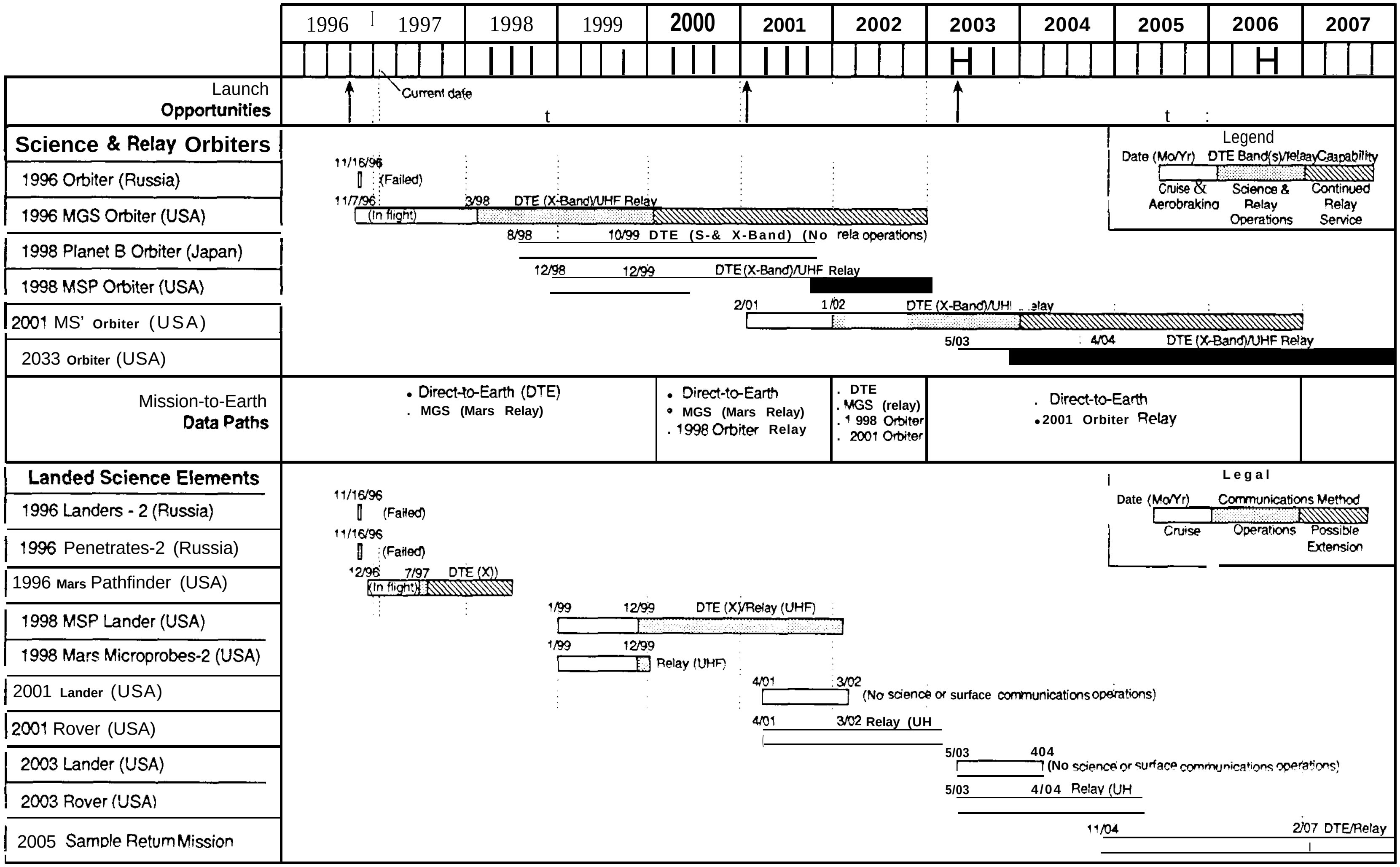

Figure 1. **Mars Exploration Mission Planning**

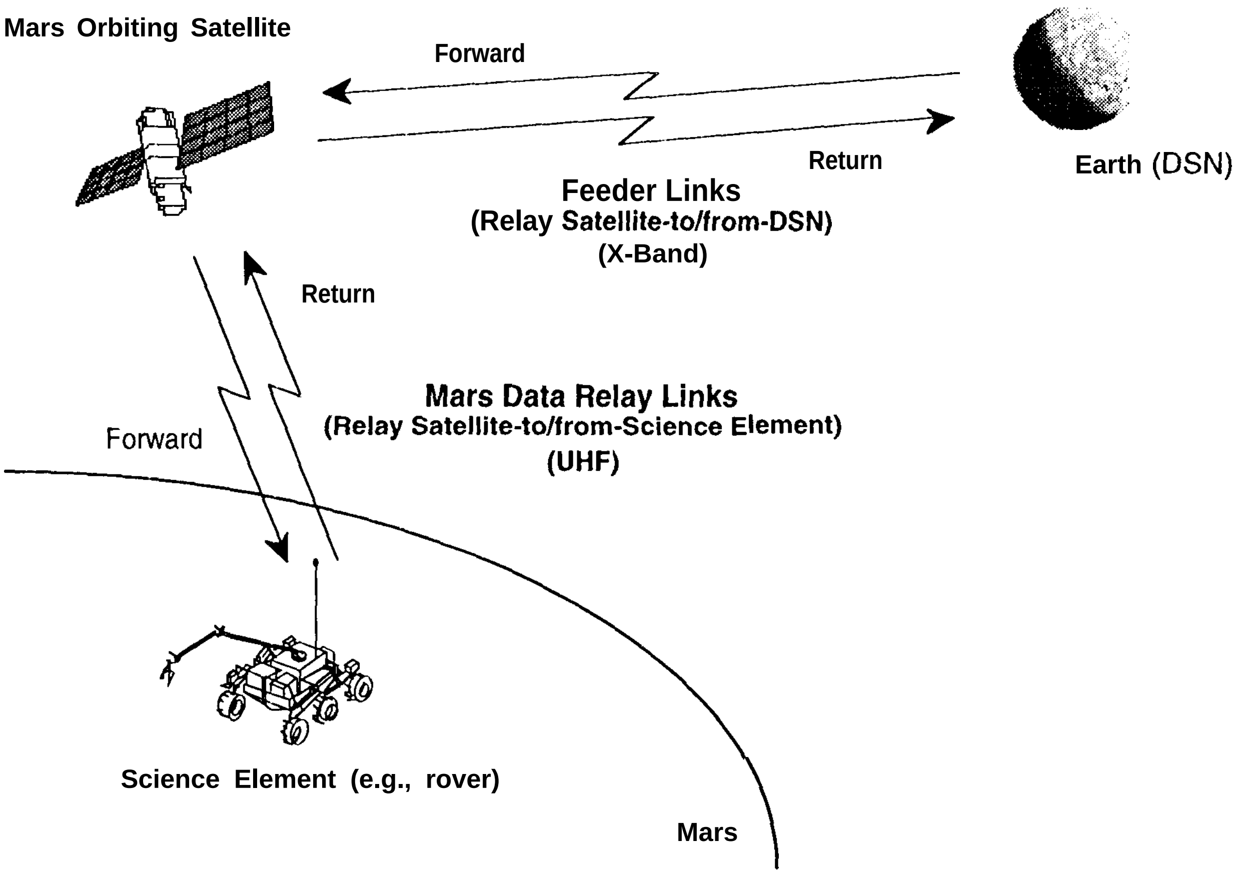

Figure 2. Mars Relay System Links

Mars Relay on the Mars Global Surveyor

The Mars Global Surveyor (MGS) spacecraft, which was launched on 7 November 1996, will carry out an extensive study of Mars using a suite of sophisticated remote-sensing instruments. The goal is to increase the understanding of Mars by mapping and surveying the planet's topography, magnetism, mineral composition, and atmosphere. Table 1 provides information about the MGS orbit. As part of the mission, a UHF communication package, known as the Mars Relay (formerly known as the Mars Balloon Relay (MBR)), provides future systems with a communications relay path.

The French space agency, Centre National d'Etudes Spatiales (CNES), originally developed the Mars Relay for the Mars Observer and Russian Mars 94/96 missions, but after the demise of Mars Observer, JPL also included the relay package on MGS. The Mars Relay employs a unique 16-second-cycle protocol, termed Balloon Telemetry Time Slot (BTTS), that uses a 4-tone forward link beacon to coordinate transmission of telemetry data from the science

Table 1. MGS Orbital Parameters

Orbit	Sun-synchronous, near circular
Altitude	378.1 km (mean)
Inclination	92.9° (near polar)
Stabilization	3-axis, nadir pointing

Table 2. MGS Mars Relay Parameters

Forward Link	
Modulation	Tones (4 square wave subcarriers)
Frequency	437.1 MHz
Data Rates	N/A
RF Power	1.3W
Coding	N/A
Return Link	
Modulation	Residual carrier BPSK
Frequency	401.5 MHz, 405.6 MHz
Data Rates	8 kbps, 128 kbps
Receiver Sensitivity	-114 dBm at 128 kbps -126 dBm at 8 kbps
Coding	Convolutional, rate 1/2, constraint length 7
Antenna	Quadrifilar helix fiberglass mast (Field of view extends from horizon to horizon with gains from -1.5 dBi to 1.5 dBi)
Data Protocol	Balloon telemetry time slot (BTTS)

elements. The series of tones on the forward link cannot send command data to the science elements. Additional parameters can be found in Table 2 [9].

The Mars Relay will provide communications for both the MSP '98 Lander (backup service) and the Mars Microprobe. It had also been expected to support elements of the Russian Mars 96 mission, which failed during launch. During its short life on the surface of Mars, the Mars Microprobe will relay science data using the Mars Relay on MGS at the 8 kbps data rate. The Mars Microprobe uses a small custom built transceiver ASIC to provide the necessary protocol and communication capabilities. Other missions launched in 1998 and 2001 may be able to utilize the Mars Relay.

Mars Surveyor '98 Orbiter Relay

The Mars Surveyor '98 Orbiter (MSP '98 Orbiter) along with its companion spacecraft, Mars Surveyor '98 Lander, comprise a mission to study the martian weather, climate, water, and carbon dioxide [4]. The orbiter will use two instruments, an imager and a radiometer, to carry out these investigations. After a launch in late 1998, the orbiter will use aerobraking to achieve an orbit similar to the MGS orbit. (See Table 1.) The orbiter carries a data relay package which was designed to support the MSP '98 Lander.

The MSP '98 Orbiter data relay capability, however, varies significantly from the Mars Relay on MGS. The MSP '98 Orbiter will carry a low-mass UHF transceiver that is a modified version of a versatile, off-the-shelf, space qualified transceiver [10]. Unlike the Mars Relay, this transceiver provides a forward data link for sending commands and operates with Frequency Shift Keying (FSK) rather than BPSK. This FSK return data relay link requires a higher received power compared to the Mars Relay. Table 3 outlines the parameters of the system.

Missions launched during the 1998 or 2001 opportunities may wish to use this relay. Mission planners, however, should closely examine any link design using this relay since the received power may make communications difficult for low-power rovers or other landers. To date, the

Table 3. MSP '98 Orbiter Relay Parameters

Forward Link	
Modulation	FSK (MSK)
Frequency	437.1 MHz
Data Rates	8 kbps, 128 kbps
RF Power	10W
Coding	None
Return Link	
Modulation	FSK (MSK)
Frequency	401.5 MHZ
Data Rates	8 kbps, 128 kbps
Receiver Sensitivity	-102 dBm at 128 kbps -109 dBm at 8 kbps
Coding	None
Antenna.	TBD
Data Protocol	Cincinnati Electronics Telemetry Broadcast Protocol (CETBP)

only mission planning to use this relay capability is the companion MSP '98 Lander. The Mars Microprobe has insufficient power to transmit to the MSP '98 Orbiter, and must relay solely on the MGS Mars Relay.

Mars Surveyor '01 and Future Orbiter Relays

The Mars Surveyor Program intends to launch additional missions during the '01, '03, and '05 opportunities. (See Figure 1.) The program may include additional long-range rovers, nanorovers, and other landed elements launched during these opportunities. The orbiter currently planned for launch in 2001 (MSP 'O 1 Orbiter) will carry several instruments for its scientific investigations. After a launch in early 2001, the orbiter will use. aerocapture and propulsive maneuvers to achieve an orbit similar to the MGS orbit. (See Table 1.) The orbiter will also serve as a data relay satellite for landed missions launching in '01 or '03. An additional orbiter may be launched in 2003 to provide dedicated data relay service to the sample return mission and surface missions launched in 2003 or later. This orbiter mission will require additional funding not currently included in the Mars Exploration Program.

The Mars program has not yet defined the data relay links for the MSP 'O 1 Orbiter. The program plans to specify these links later this year. The Mars program envisions using the same data relay link parameters selected for the MSP 'O 1 Orbiter for any subsequent relay packages on future orbiters. Table 4 outlines the preliminary data relay link design parameters. The parameters and operations of these future relay systems are expected to incorporate the principles outlined in the report of the Communication Standard Subgroup (COST) of the International Mars Exploration Working Group (IMEWG) [11]. The subgroup developed a set of principles and established a framework for standardizing the Mars data relay links. Future small robotic missions, such as rovers, microrovers, and penetrators, should plan to use these Mars data relay links as they are intended to support services for low-power, low-mass systems.

Table 4. Preliminary Mars Data Relay Link Parameters for Missions in '01 and Later

Forward Link	
Modulation	FSK (MSK)
Frequency	One channel in 400-450 MHz (TBD)
Data Rates	Several data rates up to 8 kbps (TBD)
RF Power	Mission specific but > 1 W
Coding	None or rate 1/2 convolutional coding
Return Link	
Modulation	BPSK
Frequency	Multiple channels in 400-450 MHz (TBD)
Data Rates	Several data rates up to 128 kbps (TBD)
Receiver Sensitivity	Equipment specific
Coding	None, rate 1/2 convolutional coding, or rate 1/2 convolutional coding with Reed-Solomon coding
Antenna	Mission specific
Data Protocol	TBD

Orbiter Relay Link and Rover Telecommunications

A relay link to an orbiting satellite at Mars provides dramatic performance improvement compared to a direct-to-Earth link. The range to an orbiter is a factor of >20,000 times smaller compared to the maximum Mars-Earth distance (≈ 2.6 AU). When considering that the achievable data rates vary by the square of the distance, the improvement is clearly significant. In spite of the dramatic difference in using a relay link to an orbiting satellite at Mars, rovers and other landers still require careful telecommunication design to ensure robust command (forward) and telemetry (return) data paths. Factors affecting mission design include the regularity and duration of satellite contact time, transmission power, data rates, and communication operations. The availability, cost, mass, and performance of communications equipment, including advanced micro technologies, also influence the telecommunications design of rovers and other landed elements.

The orbit of the relay satellite, rover/lander latitude, and communication restrictions on the lander affect the duration and occurrence of communication contact time between the relay satellite

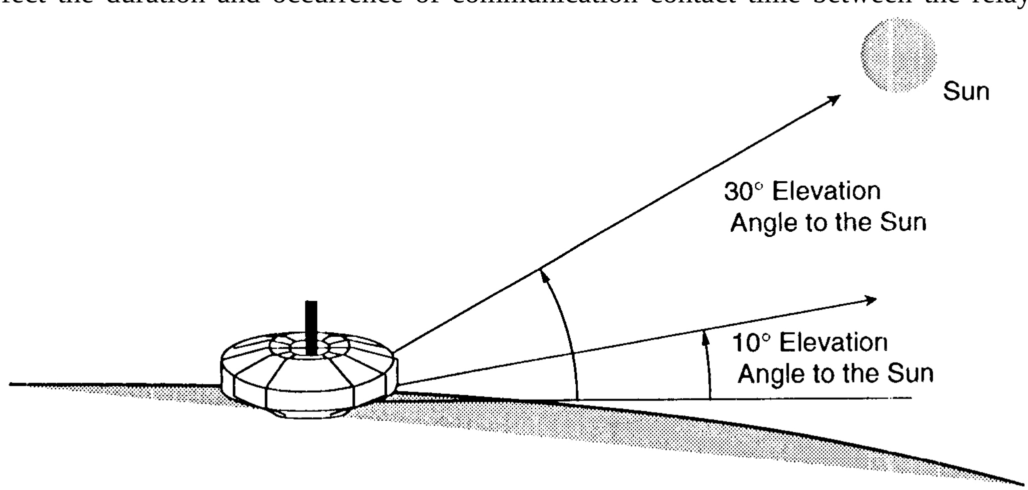

Figure 3. Lander Sun Angle Restrictions

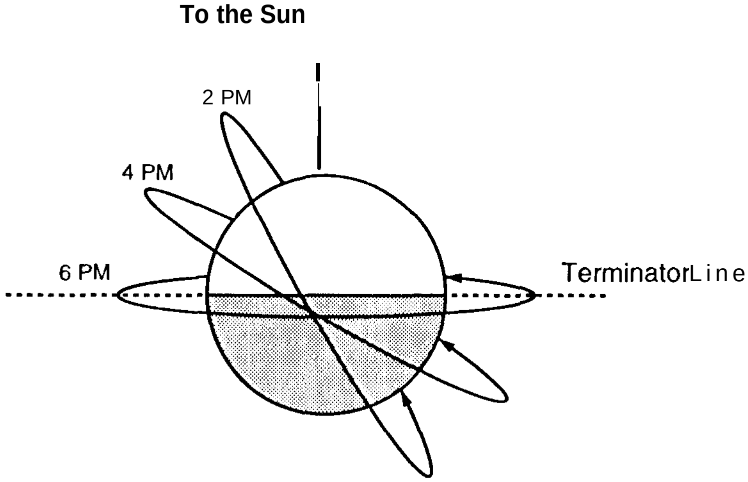

Figure 4. Relay Satellite Orbits with Different Ascending Nodes

and the lander. In general, higher altitude orbits provide more contact time to landers than do lower altitude orbits. For example, circular sun-synchronous orbits with a repeating ground path over 5 SOIS (a martian day) at altitudes of 1003 km ("Rev50"–which requires 50 orbits to repeat the ground trace) and 1710 km ("Rev40"– which requires 40 orbits to repeat the ground trace) provide increased total contact compared to the orbit planned for MGS [12]. Another factor, sun elevation, affects rovers that operate without batteries such as extremely small nanorovers. Some future rovers may only communicate when their solar arrays receive sunlight from an elevation angle above a specified value as shown in Figure 3. This operation, coupled with various ascending nodes of the relay satellite orbit (Figure 4), leads to a range of total contact time as shown in Table 5. These results are based on orbit simulations over the 6 month period (1 Jan '02 -1 Jul '02), in which martian rovers launched in '01 may operate.

Communication contact time is not the. only factor affected by the relay satellite orbit. The higher circular orbits, Rev50 and Rev40, provide daily communication contact to all locations on the surface of Mars. Lower orbits such as the MGS orbit do not provide daily coverage to some locations at latitudes within the band ±20°. The reduced contact time using lower orbit satellites,

Table 5. Total Lander to Relay Satellite Visibility (average minutes/sol (martian day))

	Orbit of Relay Satellite	MGS			Rev50			Rev40		
	Element Lattitude	**0°**	**-20°**	**-70°**	**0°**	**-20"**	**-70°**	**o'**	**-20°**	**-70°**
Lander restrictions	Ascending node									
Total contact	- Anv - - - -	**48.**	51.8	**175.7**	111.5	116.5	302.6	169.1	**177.3**	377.9
Contact when	2:00 PM	**24.**	25.8	63.0	**58.0**	58.3	109.0	82.5	103.0	135.1
sun elevation	**4:00 PM**	**24.**	25.2	59.3	52.2	51.8	106.4	84.9	88.9	132,1
>10°	**6:00 PM**	**13.**	1 4 . 6	57.3	27.1	29.0	105.2	53.3	68.2	130.7
Contact when	2:00 PM	**24.**	25.8	14.5	58.0	58.3	23.8	82.5	79.6	27.8
sun elevation	4:00 PM	17.:	17.2	12.0	30.5	**30.0**	22.4	44.3	43.3	26.7
>30	6:00 PM	**1.**	1.9	10.1	**0.0**	0.0	21.4	**0.0**	**0.0**	25.9

Note: avg./sol values for >30° is somewhat misl ıg especi lly for lower latitudes--most of ɜ visibili ; early in ıe period

Table 6. Average Data Throughput Using Mars Relay (MGS) System-Return Mars Data Relay Link (Mbytes/sol)

Fixed Condition	Elevation Angle Mask*	Variable Parameter	Element (rover) Latitude		
		EIRP	0°	-20°	-70°
Fixed data rate = 8 kbps	0°	1.8W	2.5	2.6	9.0
	20°	0.27 W	0.55	0.59	1.8
	30°	0.13W	0.28	0.30	0.87
Fixed data rate = 128 kbps	0°	35.1 w	'39.5	42.3	143.4
	20°	5.3 w	8.9	9.4	28.0
	30°	2.6 W	4.5	4.9	14.0
		Data Rate			
Fixed EIRP = 0.5 w	0"	2.2 kbps	0.67	0.72	2.5
	20°	15.1 kbps	1.0	1.1	3.3
	30"	31.0 kbps	1.1	1.2	3.4

Elevation angle mask = elevation as viewed by rover or other robotic element that the relay satellite must be above for communications
Simulation period from 1/1/02 to 7/1/02; overhead= 15%

Navigation Services for Rovers

Relay systems on-board orbiters can also provide lander and rover position determination through the use of radio metric data collected during communications opportunities with the landers. By taking Doppler and range measurements on the lander return link signals, lander positions relative to Mars can be computed. Using multiple communications opportunities, estimates of absolute lander position are possible with accuracy of< 2 km (10) [13]. The resultant accuracy, however, greatly depends on the techniques used and on other factors, including whether or not the landers implement a coherent turn-around capability (i.e., transmit a carrier coherently related to that carrier sent by the relay satellite).

Several of the relay systems intend to provide radio metric measurements for navigation services. The Mars Relay on MGS provides one-way Doppler measurements for navigation. Three one-second Doppler measurements are made for every 16-second BTTS cycle. This system provides location accuracy with an error < 1 km [14]. Relay systems on MSP 'O 1 and future orbiters also are expected to provide radio metric measurements, most likely one-way Doppler. These future relay systems may also include other methods that are not yet defined.

Operations: Automation and Protocols

Design of the in situ operations used by the relay system for communications must consider both the capabilities of the rovers as well as Earth-based operations. The key considerations for the rovers are assurance of command reception and science and engineering data return while maintaining low operational complexity and cost. The Mars Relay on the MGS and the MSP '98 Orbiter relay system use different methods while future systems may employ new space standard protocols.

The Mars Relay on MGS uses a simple poling scheme to initiate service with surface elements such as rovers. This scheme does not require knowledge of the locations of these elements. The Balloon Telemetry Time Slot (BTTS) protocol implemented by the Mars Relay segments transmissions into 16-second time slots. Although the Mars Relay only communicates with one

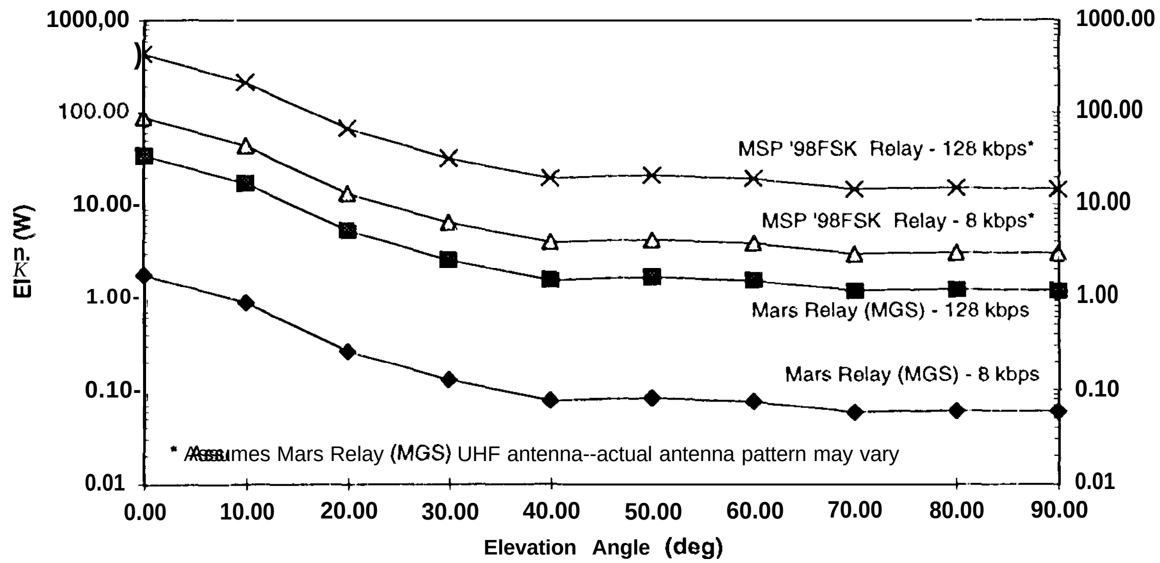

Figure 5. Return Mars Data Relay Link Transmit EIRP (3 dB margin)

however, can be partially compensated by the lower power requirements for establishing the relay link. Due to the reduced distance between the surface element and the relay satellite, the MGS orbit requires a lower transmit power from the lander for a specific data rate compared to that required for higher orbit satellites. Consequently, low power systems may use relay satellites at this low orbit.

The return link power is perhaps the most important parameter in designing links for small robotic systems, but it is not the only design parameter. Link design includes several factors such as modulation, coding, compression, antenna gain profile, and many others. Figure 5 provides a comparison of the MGS Mars Relay and MSP '98 Orbiter return Mars data relay link and the associated requirements for the lander communication systems. As Figure S indicates, the effective isotropic radiated power (EIRP) required can vary significantly depending on the link parameters such as modulation and data rate.

In the end, providing sufficient command data to the surface element and returning science and engineering data from this element are the primary goals of the relay telecommunications system. The total data throughput includes the effects of coverage time, data rate, and other effects such as compression and overhead due to protocols and coding. For example, the average data transferred from a surface element to Earth per sol (martian day) for an 8 kbps link (15% overhead, no compression) using the Mars Relay (MGS) system is 2.5 Mbytes at 0° latitude and 9.0 Mbytes at -70° latitude. Table 6 lists these and other average data values (Mbytes/sol) for the return Mars data relay link given various fixed conditions (data rate or EIRP) for a rover or other robotic element. Assuming the Mars Relay (MGS) system, Table 6 provides rover telecommunication designers with the trade-offs for various factors including data rate, EIRP, and the elevation mask at which a rover can communicate to the relay spacecraft. Several additional factors not shown in Table 6 may limit the total data return including the lander's restrictions for sun elevation and the relay satellite's servicing of multiple systems that may result in more data than the relay satellite's constrained return link to Earth can handle.

To benefit from this data relay service requires the development of telecommunications systems for the science elements that not only meet the communication requirements but also satisfy the environmental and mission constraints such as mass and cost. Current advances in communication design improve performance using low-power, low-mass systems. JPL, through its microelectronics programs is currently developing micro technologies that will make even smaller systems available for rovers and other constrained missions.

rover during a time slot, consecutive time slots may be allocated to the same rover or may alternate between two rovers. The Mars Relay may communicate with up to 3 different landers that are simultaneously in view using its 4-tone forward link and alternating time slots. The poling performed by the Mars Relay is selected by command from the Earth.

Systems using the MSP '98 Orbiter relay system are expected to schedule service times for relay operations. The Earth-based operations centers will schedule service times and up-load these commands to the spacecraft, The actual protocol used for relay operations, however, is the Cincinnati Electronic Telemetry Broadcast Protocol (CETBP) that provides error-free data transfer using a full-duplex handshaking scheme with a 17% reduction of the data rate. The relay system can also operate in a continuous mode that does not guarantee error-free data. The CETBP provides unique addressing thus allowing service to multiple rovers.

For future relay systems, autonomous in situ command and data collection operations between the relay satellite and surface elements are desired to reduce the Earth-based operations. Use of handshaking protocols including evolving space standard protocols can provide simultaneous error-free data transmission to and from multiple spacecraft, but simple half-duplex schemes may be required for constrained missions. Autonomous operations may be particularly important for extremely constrained missions such as balloons and microrovers. The protocol and operations method for the MSP 'O 1 Orbiter relay system have not been defined at this time.

Summary

The recent launches of Mars Pathfinder and Mars Global Surveyor (MGS) have begun the next generation of Mars exploration and opened up new opportunities for surface and atmospheric robots to explore our neighboring planet. An important element of this program is the inclusion of relay capability on orbiting satellites; this will enable small robotic missions to receive commands and transmit science and engineering data that would not be possible using direct-to-Earth links. The orbiting missions—MGS, Mars Surveyor Program (MSP) '98 Orbiter, and MSP 'O 1 Orbiter—and their UHF communications packages will be equipped to provide relay links with landed elements at Mars. Developers of future robotic elements for operations on or near the surface of Mars, such as rovers, landers, and balloons, should review their telecommunications requirements relative to the proposed relay link capabilities of future Mars orbiters, and, if appropriate, influence the specification of these relay systems. The telecommunications relay and navigation support provided by the orbiting systems heralds new opportunities to explore the red planet with smaller and lower-cost missions.

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